Overview of the Global Precipitation Measurement Mission (GPM) and Products

George J. Huffman(1)

[and David T. Bolvin(1,2), Dan Braithwaite(3), Kuolin Hsu(3), Robert Joyce(4,5), Christopher Kidd(1,6), Eric Nelkin(1,2), Soroosh Sorooshian(3), Pingping Xie(5), Jackson Tan(1,7)]

(1) NASA/GSFC Earth Sciences Division – Atmospheres
(2) Science Systems and Applications, Inc.
(3) Univ. of California Irvine
(4) Innovim
(5) NOAA/NWS Climate Prediction Center
(6) Univ. of Maryland / ESSIC
(7) Univ. Space Res. Assoc.

george.j.huffman@nasa.gov

1. Introduction – GPM Core Observatory

Launch: Feb. 27, 2014

Altitude: 407 km

Orbit inclination: 65˚

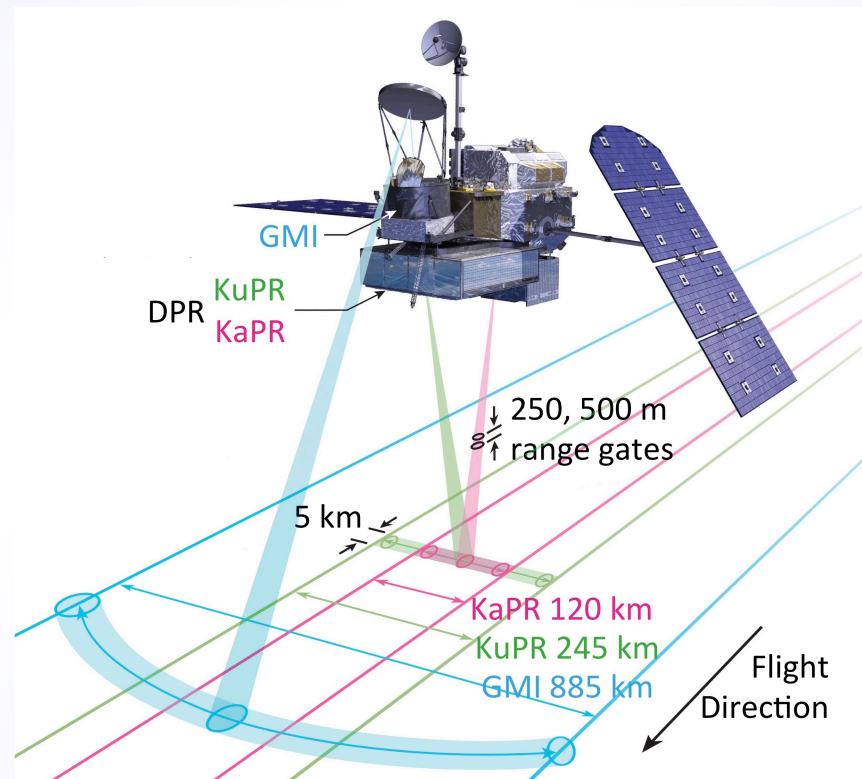3-year design life, extra fuel

Measurement range: 0.2-110 mm/hr & snow detection

GPM Microwave Imager (GMI) – NASA

- Passive radiometer with excellent calibration
- 13 channels: 10VH, 19VH, 23, 36VH, 89VH, 166VH, 183±3, ±7
- observations of precipitation intensity and distribution over 885 km swath
- some footprints at ~5 km size

Dual-frequency Precipitation Radar (DPR) – JAXA)

- KuPR similar to TRMM, KaPR added for GPM
- 3D measurements of precipitation structure, precipitation particle size distribution
- 5 km horizontal, 250 m vertical resolution
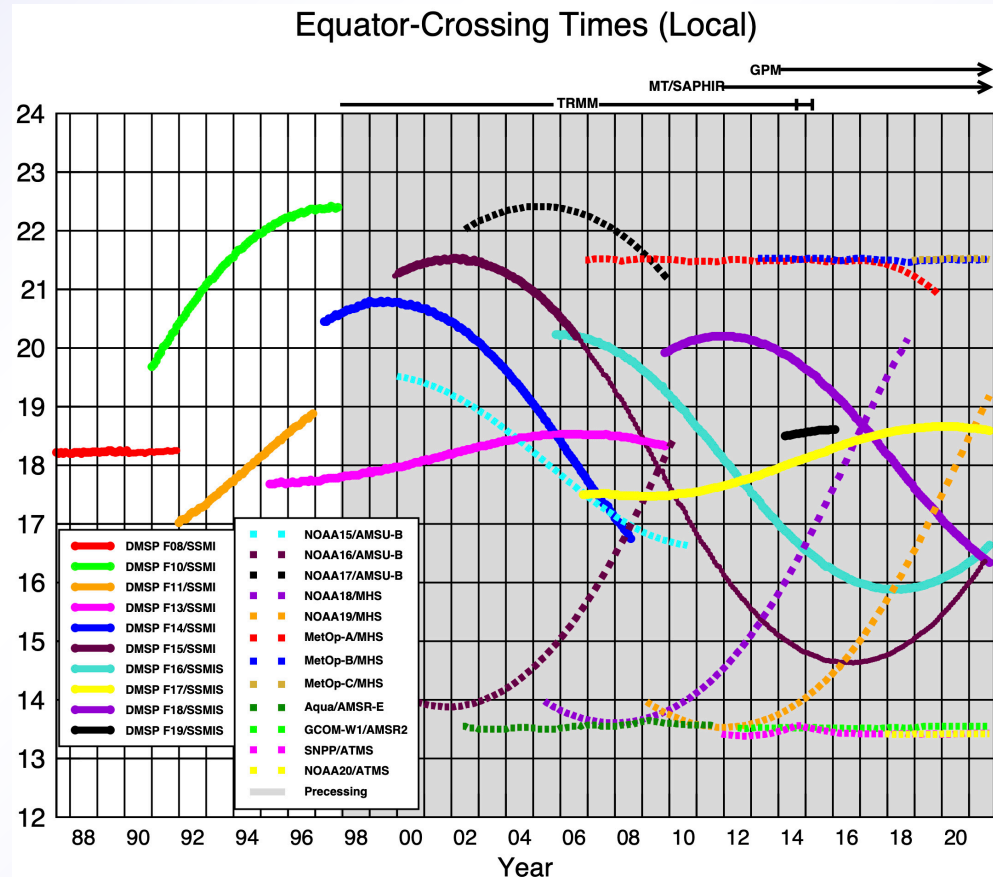
1. Introduction – The Constellation

Presently 3-hourly observations >90% of the time, globally

The current GPM constellation includes:

- 5 passive microwave imagers
- 6 passive microwave sounders
- input taken as <u>precip</u> estimates
  - GPROF (LEO PMW) + PRPS (SAPHIR)
  - PERSIANN-CCS (GEO IR)
  - CORRA (combined PMW-Ku radar)
  - GPCP SG (monthly satellite-gauge)

The constellation is evolving

- launch manifests are assured for sounders, sparse for imagers
- how will we cope with short-lived smallsats?

Equator-Crossing Times (Local)

DMSP F08/SSMI	NOAA15/AMSU-B
DMSP F10/SSMI	NOAA16/AMSU-B
DMSP F11/SSMI	NOAA17/AMSU-B
DMSP F13/SSMI	NOAA18/MHS
DMSP F14/SSMI	NOAA19/MHS
DMSP F15/SSMI	MetOp-A/MHS
DMSP F16/SSMIS	MetOp-B/MHS
DMSP F17/SSMIS	MetOp-C/MHS
DMSP F18/SSMIS	Aqua/AMSR-E
DMSP F19/SSMIS	GCOM-W1/AMSR2
	SNPP/ATMS
	NOAA20/ATMS
	Precessing

Ascending passes (F08 descending); satellites depicted above graph precess throughout the day.
Image by Eric Nelkin (SSAI), 12 October 2021, NASA/Goddard Space Flight Center, Greenbelt, MD.

2. From Data to Estimates – Single-satellite estimates

Nearly coincident views by 5 sensors southeast of Sri Lanka

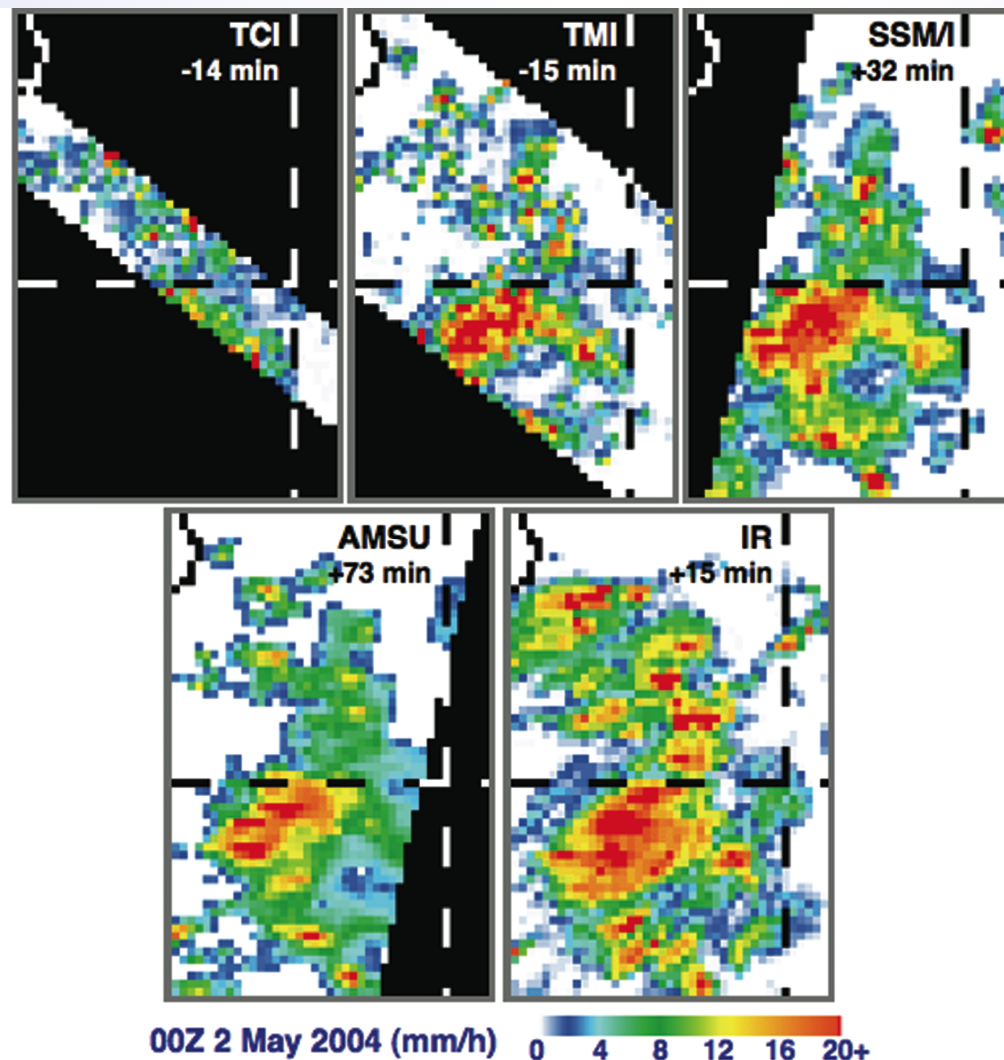The offset times from 00Z are below the "sensor" name

The estimates are related, but differ due to

- time of observation
- resolution
- sensor/algorithm limitations

The GPM web site has a master directory of the individual satellite products at

- *https://gpm.nasa.gov/data/directory*
- Level 1, 2, 3 (sensor, geophysical, gridded)

Combination schemes try to work with all of these data to create a uniformly gridded product

00Z 2 May 2004 (mm/h)   0 4 8 12 16 20+

3. IMERG – Quick description (1/2)

IMERG is a <u>unified U.S. algorithm</u>

- based on code from NASA, NOAA, and U.C. Irvine
- processed at PPS (GSFC)

IMERG is a single integrated code system

- multiple runs for different user requirements for latency and accuracy
  - "Early" – 4 hr (flash flooding)
  - "Late" – 14 hr (crop forecasting)
  - "Final" – 3 months (research)
- time intervals are half-hourly and monthly (Final only)
- 0.1° global CED grid
  - <u>morphed precip</u> 90° N-S, frozen surface masked out
  - IR covers 60° N-S

Datasets listed in *https://gpm.nasa.gov/data/directory*

- access to alternate formats at PPS, GES DISC
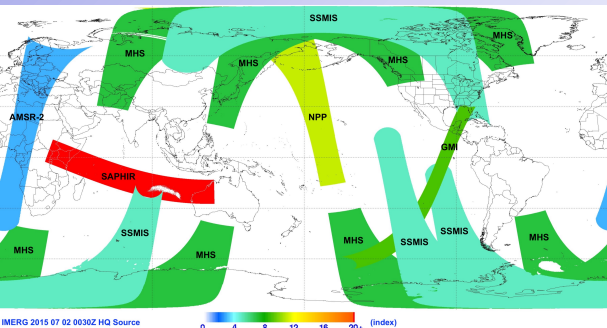- documentation

	Half-hourly data file (Early, Late, Final)
1	*[multi-sat.] precipitationCal*
2	[multi-sat.] precipitationUncal
3	*[multi-sat. precip] randomError*
4	[PMW] HQprecipitation
5	[PMW] HQprecipSource [identifier]
6	[PMW] HQobservationTime
7	IRprecipitation
8	IRkalmanFilterWeight
9	*[phase] probabilityLiquidPrecipitation*
10	*precipitationQualityIndex*
	Monthly data file (Final)
1	*[sat.-gauge] precipitation*
2	*[sat.-gauge precip] randomError*
3	GaugeRelativeWeighting
4	*probabilityLiquidPrecipitation [phase]*
5	*precipitationQualityIndex*

3. IMERG – Quick description (2/2)

<u>Overall calibration</u> is provided by TRMM and GPM Combined Radar-Radiometer Algorithm (<u>CORRA</u>)

- <u>TRMM</u> June 2000-May 2014, <u>GPM</u> thereafter
- TRMM-era microwave calibrations over <u>33ºN-S</u> and
- blend with adjusted monthly <u>climatological GPM-era microwave calibrations over 25º-90º N and S</u>

<u>IMERG is adjusted to GPCP monthly climatology</u> zonally to achieve a "reasonable" bias profile

- the GPM core product biases are similar (by design)
  - these profiles are systematically low in the extratropical oceans compared to
    - <u>GPCP</u> monthly Satellite-Gauge product is a community standard climate product
    - Behrangi Multi-satellite CloudSat, TRMM, GPM (<u>MCTG</u>) product
- over land this provides a first cut at the adjustment to gauges that the final calibration in IMERG enforces
- similar issue in the TRMM era

	Half-hourly data file (Early, Late, Final)
1	*[multi-sat.] precipitationCal*
2	[multi-sat.] precipitationUncal
3	*[multi-sat. precip] randomError*
4	[PMW] HQprecipitation
5	[PMW] HQprecipSource [identifier]
6	[PMW] HQobservationTime
7	IRprecipitation
8	IRkalmanFilterWeight
9	*[phase] probabilityLiquidPrecipitation*
10	*precipitationQualityIndex*
	Monthly data file (Final)
1	*[sat.-gauge] precipitation*
2	*[sat.-gauge precip] randomError*
3	GaugeRelativeWeighting
4	*probabilityLiquidPrecipitation [phase]*
5	*precipitationQualityIndex*

3. IMERG – Examples of Data Fields

IMERG 2015 07 02 0030Z HQ Source

IMERG 2015 07 02 0030Z IR Precipitation Rate

IMERG 2015 07 02 0030Z PrecipitationCal Rate

IMERG 2015 07 02 0030Z HQ Time

IMERG 2015 07 02 0030Z HQ Precipitation Rate

IMERG 2015 07 02 0030Z Kalman IR Weight

IMERG V06 2015 07 02 0030Z Quality Index

PMW
sensor

IR precip

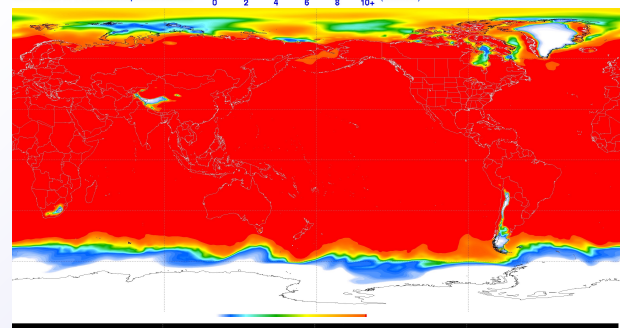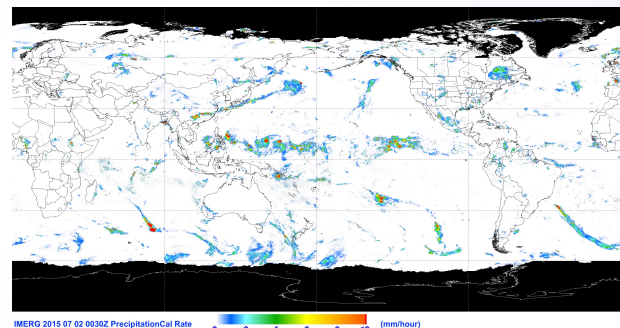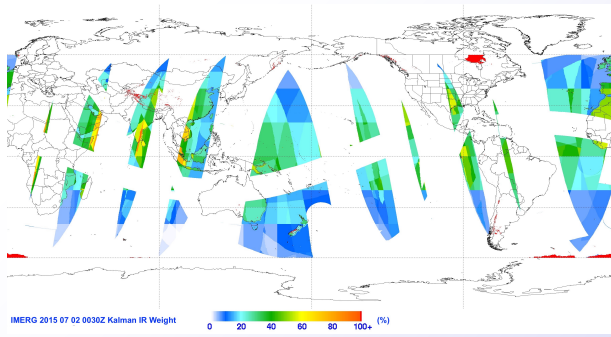cal precip
(uncal precip)

PMW
time into
half hour

**2 July 2015
0030 UTC**

probability of
liquid phase
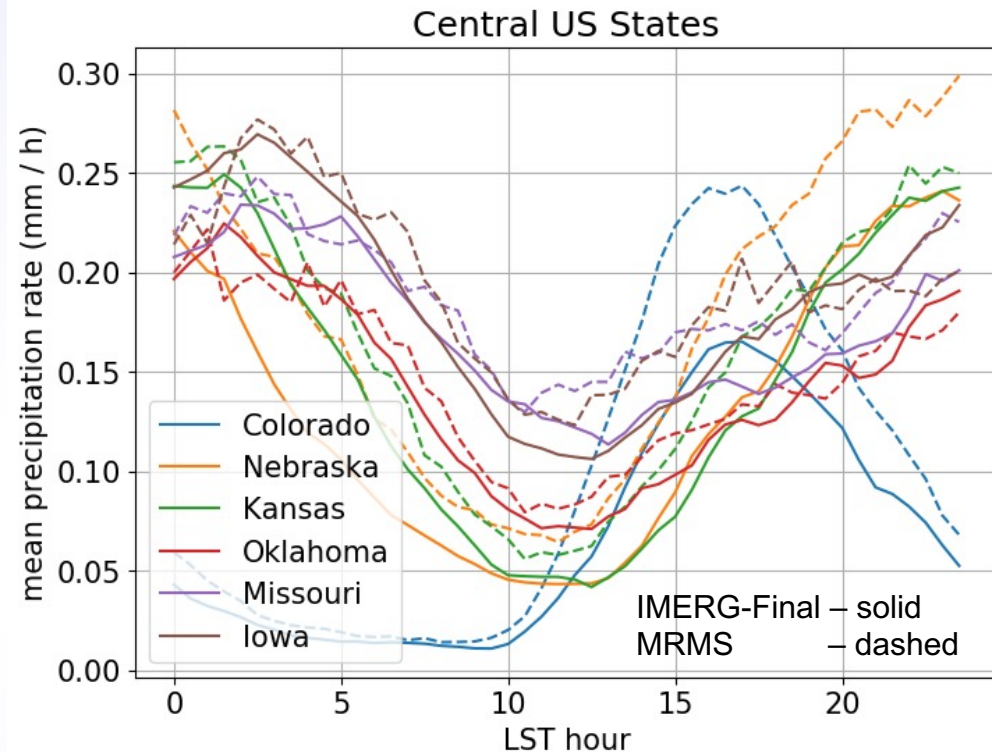
PMW
precip

IR weight

Quality
Index

4. Results – Final Run, June-August Diurnal Cycle in Central U.S. (GPM Era)

Average June-August for 2014 to 2018 (5 summers) for 6 states, Final Run

Compared to Multi-Radar Multi-Sensor (MRMS, dashed), Final (solid) shows:

- lower averages (despite use of gauge data)
- lower amplitude cycle in Colorado
- higher amplitude cycle in Iowa
- very similar curve shapes, peak times
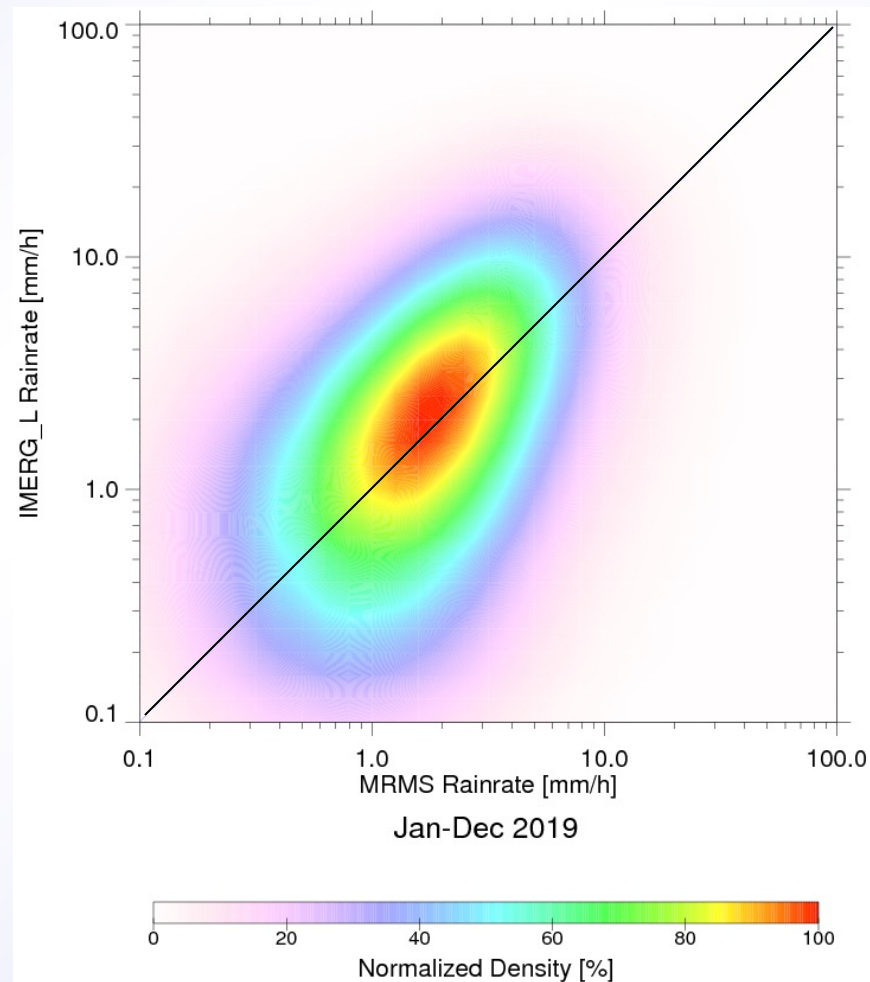- earlier in Colorado, later in Iowa, Missouri

Central US States

IMERG-Final – solid
MRMS – dashed

Legend: Colorado, Nebraska, Kansas, Oklahoma, Missouri, Iowa

J. Tan (USRA; GSFC)

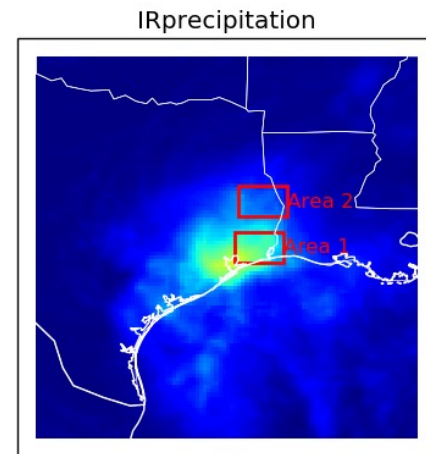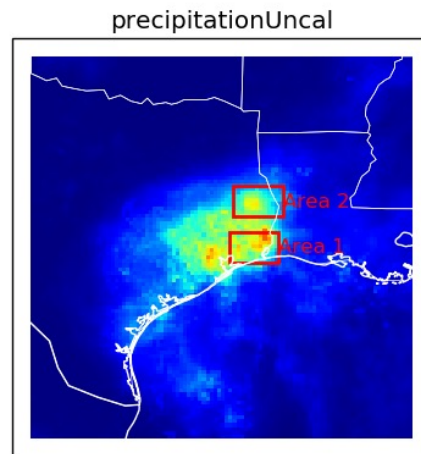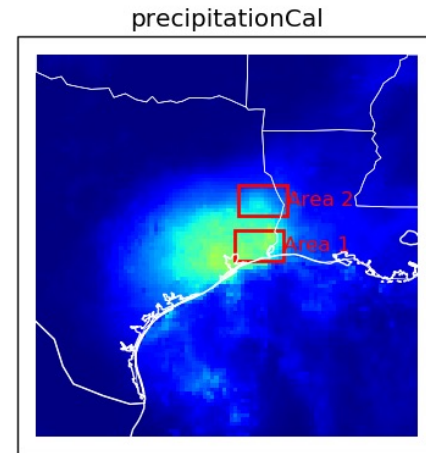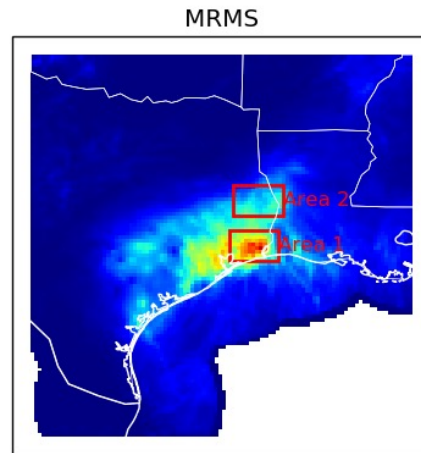IMERG bias varies by location and weather regime, but in general

- comparison to MRMS over CONUS at half-hourly 0.1° scale for January-December 2019
- low(high) at low(high) end
- mean positive bias
- this particularly affects applications that depend on extremes, like flooding
- tracking down the high bias has proved "challenging"

Jan-Dec 2019

GPM GV Office

Harvey loitered over southeast Texas for a week

- MRMS considered the best estimate
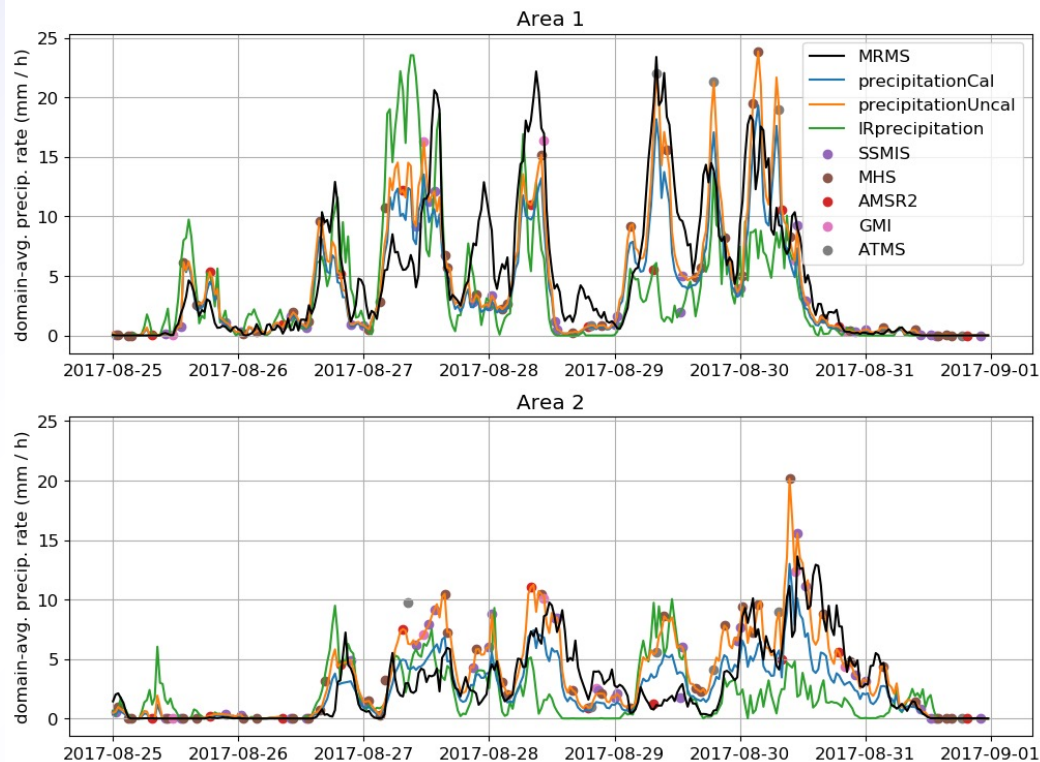 - some questions about the details of the gauge calibration of the radar estimate
  - over land
- Uncal (just the intercalibrated satellite estimates) under(over)-estimated in Area 1(2)
  - should be similar to Late Run
- Cal (with gauge adjustment) pulls both areas down
- microwave-adjusted PERSIANN-CCS IR has the focus too far southwest

Huffman et al. (2020) and J. Tan (USRA; GSFC)

IMERG largely driven by microwave overpasses (dots)

- except duplicate times
- not just time interpolation
  - systems move into / out of the box between overpasses
- satellites show <u>coherent differences</u> from MRMS
  - PMW only "sees" the solid hydrometeors (scattering channels), since over land
  - IR looks at Tb within "clustered" data
  - both are calibrated to statistics of time/space cubes of data
    - Cal is basically *(Uncal x factor)*
- short-interval differences show <u>some cancellation</u> over the whole event
  - but <u>several-hour differences</u> can be dramatic

Huffman et al. (2020) and J. Tan (USRA; GSFC)

5. Looking Ahead to Version 07

Input data issues

- quality control for GOES-W noise

- more-advanced IR algorithm: Precipitation Estimations from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN) Dynamic Infrared–Rain rate model (PDIR)

- assess the degree to which GPROF MW estimates can be used over snow/ice surfaces

    - early indications that estimates are useful over "warm" snow/ice surfaces

    - gaps will still exist in coldest regions

Multi-satellite issues

- raise all caps on precipitation rate to 200 mm/hr

- add more inputs to compute morphing vectors

- variable name changes   HQprecipitation   ➔ MWprecipitation

                          HQobservationTime   ➔ MWobservationTime

                          HQprecipSource   ➔ MWprecipSource

                          precipitationCal   ➔ precipitation

                          IRkalmanFilterWeight   ➔ IRinfluence

- SHARPEN = Scheme for Histogram Adjustment with Ranked Precipitation Estimates in the Neighborhood

5. Looking Ahead to Version 07 – SHARPEN

- undo distortion of PDF when <u>averaging</u> precipitation during morphing
- use <u>local quantile mapping</u> from morphed to input PDFs
- the datasets input to the Kalman filter have similar PDFs (top row)
- the Kalman-filtered result (d) has larger coverage, lower maximum rates because it's a weighted average
- <u>the SHARPEN'ed precipitation PDF (e) is closer to the input precipitation PDFs</u>

Example over West Africa for 00:00-00:30 UTC, 1 July 2018. The blue square in (e) shows the size of the "local" 25x25 template. [Tan et al. 2021]

5. Looking Ahead to Version 07 – Schedule

TMPA ended with December 2019

- the products are still available, but users are encouraged to move to IMERG

The Version 07 release is happening later than originally planned (and still in flux)

- 6 December: radar reprocessing starts
- 1 February: GPROF and Combined reprocessings start
- 1 May: IMERG reprocessing starts, but
- 6 December: IMERG Early and Late Runs must shift from V06 to V07 Combined near-real-time input old GPROF feeds Combined until 1 February

Radar/GPROF/Combined	V06	V07
IMERG Early/Late	V06	V06 Algorithm / V06/V07 Input	V07
IMERG Final	V06	V07

6 Dec 2021   1 May 2022

Questions? george.j.huffman@nasa.gov
Also see our virtual poster H15Q-1239, Abstract ID 840179
On the Verge of IMERG Version 07, Monday, 13 Dec., 1600-1800 CST

6. References

Bolvin, D.T., G.J. Huffman, E.J. Nelkin, J. Tan, 2021: Comparison of Monthly IMERG Precipitation Estimates with PACRAIN Atoll Observations. *J. Hydrometeor.*, **22**, 1745-1753. *doi:10.1175/JHM-D-20-0202.1*

Huffman, G.J., D.T. Bolvin, D. Braithwaite, K. Hsu, R. Joyce, C. Kidd, E.J. Nelkin, S. Sorooshian, E.F. Stocker, J. Tan, D.B. Wolff, P. Xie, 2020: Integrated Multi-satellitE Retrievals for the Global Precipitation Measurement (GPM) mission (IMERG). Chapter 19 in *Adv. Global Change Res., Vol. 67, Satellite Precipitation Measurement*, V. Levizzani, C. Kidd, D. Kirschbaum, C. Kummerow, K. Nakamura, F.J. Turk (Ed.), Springer Nature, Dordrecht, ISBN 978-3-030-24567-2 / 978-3-030-24568-9 (eBook), 343-353. *doi:/10.1007/978-3-030-24568-9_19*

Potter, G., G.J. Huffman, D.T. Bolvin, M.G. Bosilovich, J. Hertz, Laura E. Carriere, 2020: Histogram Anomaly Time Series: A Compact Graphical Representation of Spatial Time Series Data Sets. *Bull. Amer. Meteor. Soc.*, **101**, E2133-E2137. *doi:10.1175/BAMS-D-20-0130*

Rajagopal, M., E. Zipser, G.J. Huffman, J. Russell, J. Tan, 2021: Comparisons of IMERG Version 06 Precipitation At and Between Passive Microwave Overpasses in the Tropics. *J. Hydrometeor.*, **22**(8), 2117–2130. *doi:10.1175/JHM-D-20-0226.1*

Tan, J., G.J. Huffman, D.T. Bolvin, E.J. Nelkin, M. Rajagopal, 2021: SHARPEN: A Scheme to Restore the Distribution of Averaged Precipitation Fields. *J. Hydrometeor.*, **22**(8), 2105–2116. *doi:10.1175/JHM-D-20-0225.1*

Questions? george.j.huffman@nasa.gov

5. Looking Ahead to Version 07 – Schedule

TMPA ended with December 2019

- the products are still available, but users are encouraged to move to IMERG

The Version 07 release is happening later than originally planned (and still in flux)

- 6 December: radar reprocessing starts
- 1 February: GPROF and Combined reprocessings start
- 1 May: IMERG reprocessing starts, but
- 6 December: IMERG Early and Late Runs must shift from V06 to V07 Combined near-real-time input old GPROF feeds Combined until 1 February

Questions? george.j.huffman@nasa.gov
Also see our virtual poster H15Q-1239, Abstract ID 840179
On the Verge of IMERG Version 07, Monday, 13 Dec., 1600-1800 CST
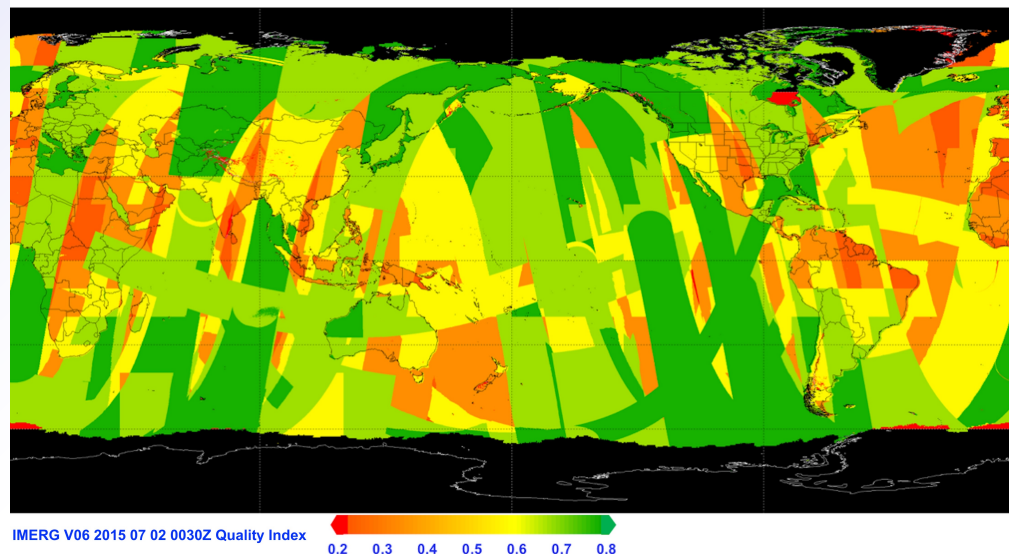
Supplemental Material

2. IMERG – Quality Index (1/2)

Half-hourly QI (revised)

- approx. Kalman Filter correlation
  - based on
    - times to 2 nearest PMWs (only 1 for Early) for morphed data
    - IR at/near time (when used)

$$QI_h = tanh\left(\sqrt{\sum arctanh^2(r_i)}\right)$$

  - where r is correlation, and the i's are for forward propagation, backward propagation, and IR
  - or, an approximate correlation when a PMW is used for that half hour
- revised to 0.1° grid (0.25° in V05)
- thin strips due to inter-swath gaps
- blocks due to regional variations
- snow/ice masking will drop out microwave values

IMERG V06 2015 07 02 0030Z Quality Index

0.2 0.3 0.4 0.5 0.6 0.7 0.8

D.Bolvin (SSAI; GSFC)

The goal is a simple "stoplight" index

- ranges of QI will be assigned
  - good   0.6-1
  - use with caution 0.4-0.6
  - questionable   0-0.4
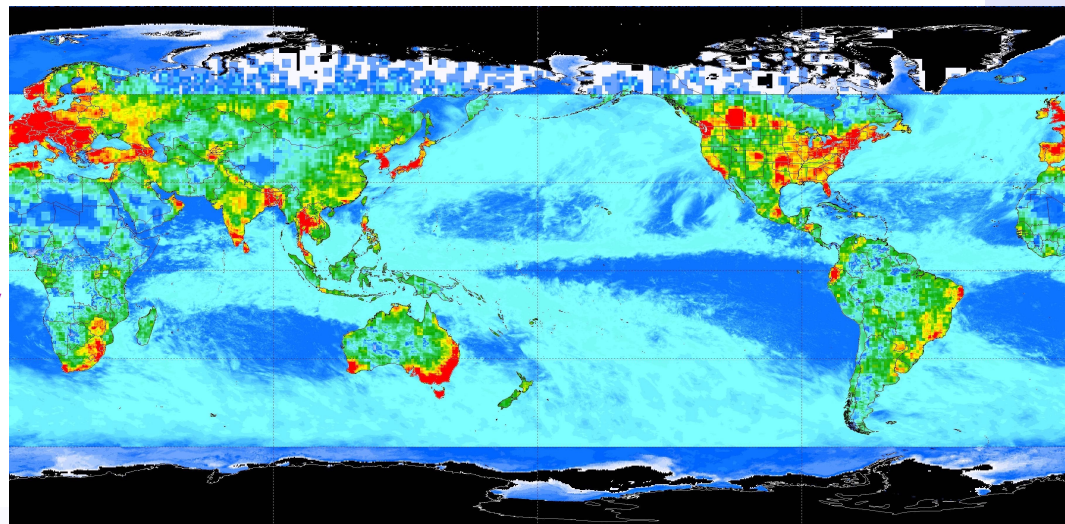 - is this a useful parameter?

Monthly QI (unchanged)

- Equivalent Gauge (Huffman et al. 1997) in gauges / 2.5°x2.5°

$$QI_m = (S + r) * H * (1 + 10 * r^2)/e^2$$

  - where r is precip rate, e is random error, and H and S are source-specific error constants
- invert random error equation
- largely tames the non-linearity in random error due to rain amount
- some residual issues at high values
- doesn't account for bias
- the stoplight ranges are

  - good   > 4
  - use with caution   2-4
  - questionable   < 2
  - note that this ranking points out uncertainty in the values in light-precip areas that nearly or totally lack gauges (some deserts, oceanic subtropical highs)
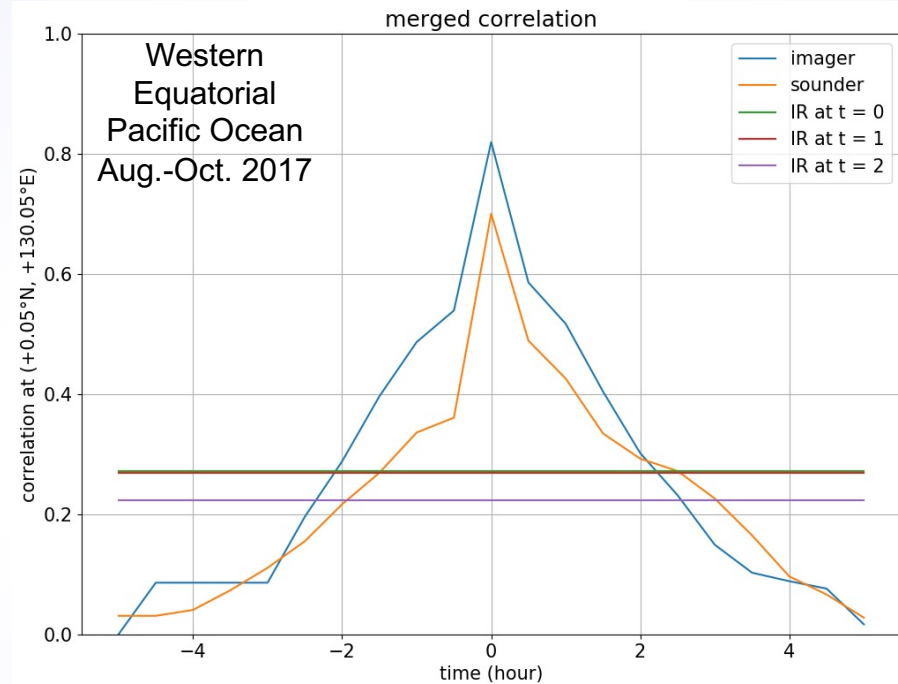

Month Qual. Index Dec 2016

D.Bolvin (SSAI; GSFC)

0   4   8   12   16   20+

Following the CMORPH approach

- for a given time offset from a microwave overpass
- compute the (smoothed) average correlation between
  - morphed microwave overpasses and microwave overpasses at that time offset, and
  - IR precip estimates and microwave overpasses at that time offset and IR at 1 and 2 half hours after that time offset
  - for conical-scan (imager) and cross-track-scan (sounder) instruments separately
- the microwave correlations drop off from t=0, dropping below the IR correlation within a few hours (2 hours in the Western Equatorial Pacific)
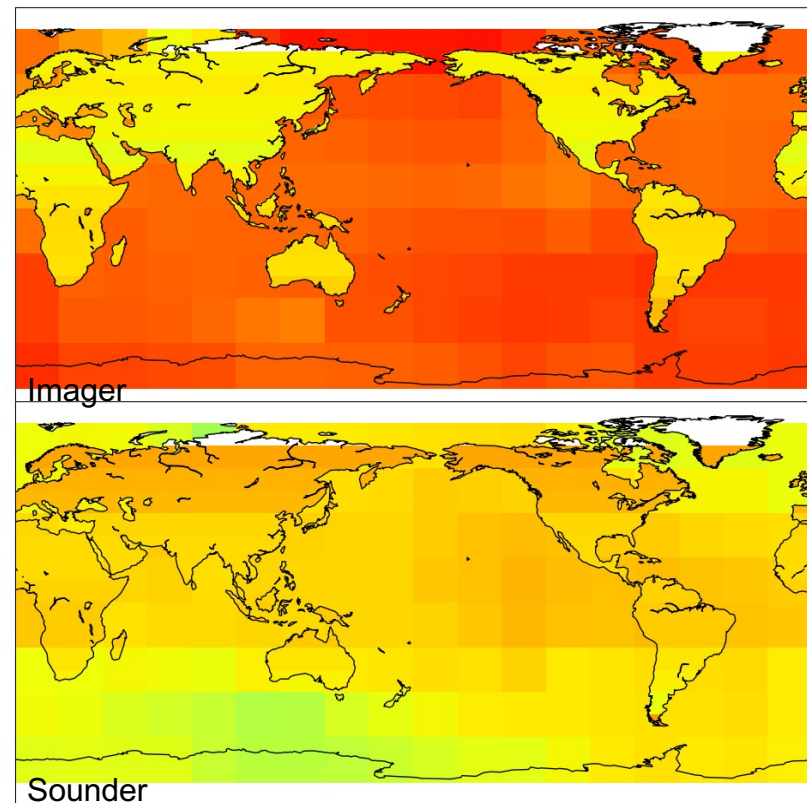

J. Tan (USRA; GSFC)

Following the CMORPH approach

- for a given time offset from a microwave overpass
- compute the (smoothed) average correlation between
  - morphed microwave overpasses and microwave overpasses at that time offset, and
  - IR precip estimates and microwave overpasses at that time offset and IR at 1 and 2 half hours after that time offset
  - for conical-scan (imager) and cross-track-scan (sounder) instruments separately
- the microwave correlations drop off from there, dropping below the IR correlation within a few hours (2 hours in the Western Equatorial Pacific)
- at t=0 (no offset), imagers are better over oceans, sounders are better or competitive over land

Imager

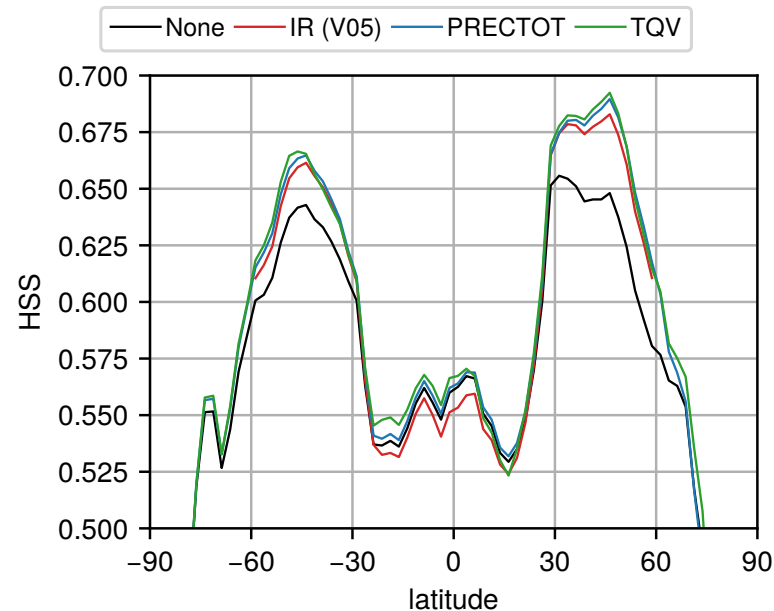Sounder

L2 correlation at t=0 Aug.-Oct. 2017

J. Tan (USRA; GSFC)

Tested vectors computed on a 5°x5° template every 2.5°, interpolated to 0.1°x0.1° based on

- MERRA2 TQV (vertically integrated vapor)
- MERRA2 PRECTOT (precip)
- CPC 4-km merged IR Tb (as in V05 IMERG)
- NULL (no motion)

On a zonal-average basis, compute the Heidke Skill Score for

- merged GPROF precip (HQ) propagated for 30 min.
- compared to HQ precip observed in the following 30 min.
- TQV is consistently at/near the top
- further research is expected for V07

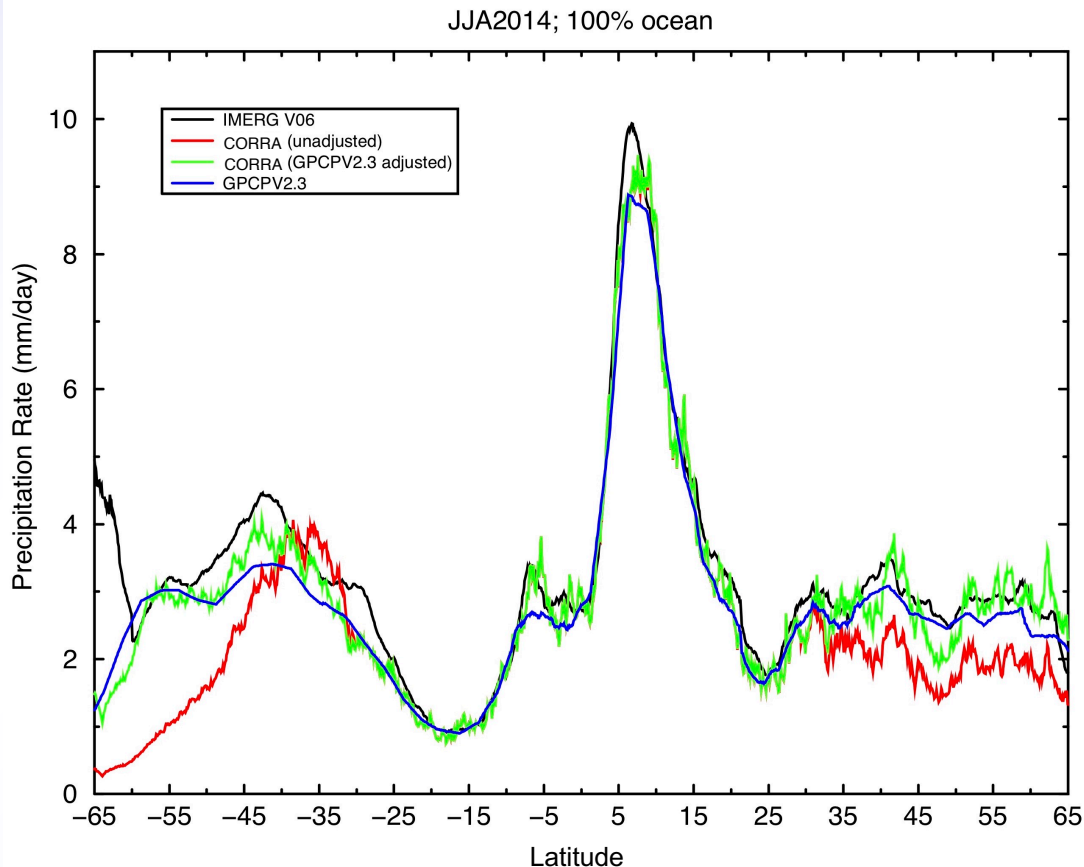J. Tan (USRA; GSFC)

4. Results – Calibration

Calibration sequence is

- CORRA <u>climatologically</u> calibrated to GPCP over ocean outside 30ºN-S
- TMI/GMI calibrated to CORRA
- GPM constellation <u>climatologically</u> calibrated to TMI/GMI

Adjustments working roughly as intended

- CORRA is low at higher latitudes
- adjustments in Southern Ocean are large and need analysis
  - IMERG subsetted to coincidence with CORRA is much closer to CORRA

JJA2014; 100% ocean

Legend:
- IMERG V06
- CORRA (unadjusted)
- CORRA (GPCPV2.3 adjusted)
- GPCPV2.3

D. Bolvin (SSAI; GSFC)

4. Results – Ocean (50°N-S) Precip Timeseries

V06 Final Run starts June 2000

V06 is <u>higher</u> than 3B43 (TMPA) and GPCP <u>over ocean</u>

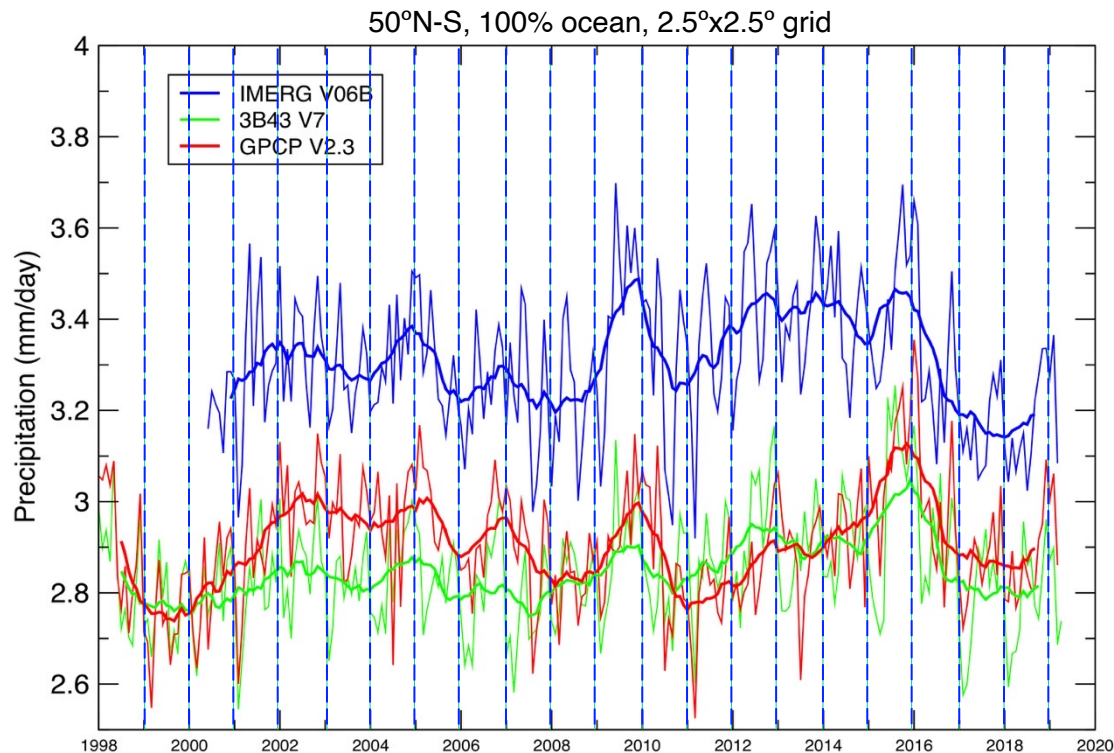<u>TRMM-era</u> IMERG has a strong <u>semi-annual</u> signal

- <u>GPM-era</u> IMERG and <u>3B43</u> dominated by the <u>annual</u> cycle

Interannual variation

- has similar peaks/troughs for all datasets
- GPCP (<u>passive microwave</u> calibration) <u>lags</u> phase of 3B43 (through 2013), IMERG (both <u>PMW/radar</u> calibration)
- after September 2014, 3B43 (PMW calibration) matches GPCP phase

Additional multi-year variations

- IMERG and 3B43 are High Resolution Precipitation Products, not CDRs

50°N-S, 100% ocean, 2.5°x2.5° grid

E. Nelkin (SSAI; GSFC)

4. Results – Tropical Ocean (20ºN-S) Monthly Precip Histogram Timeseries

Histogram of Final Run <u>monthly</u> tropical oceanic precip on 0.1º grid, 20º N-S (top)

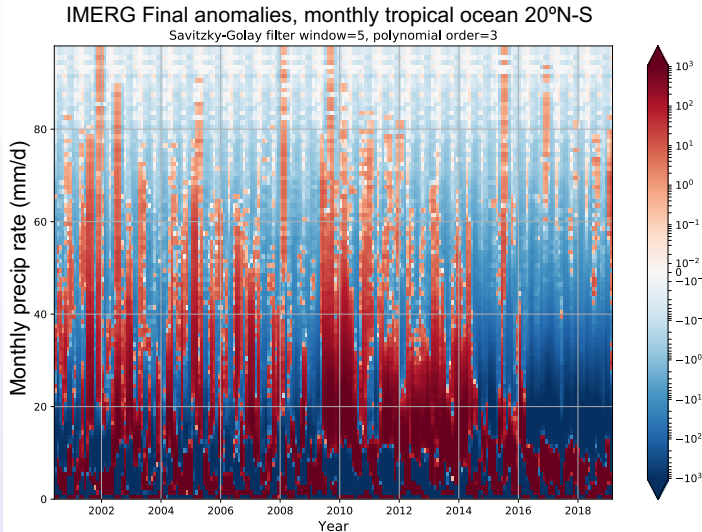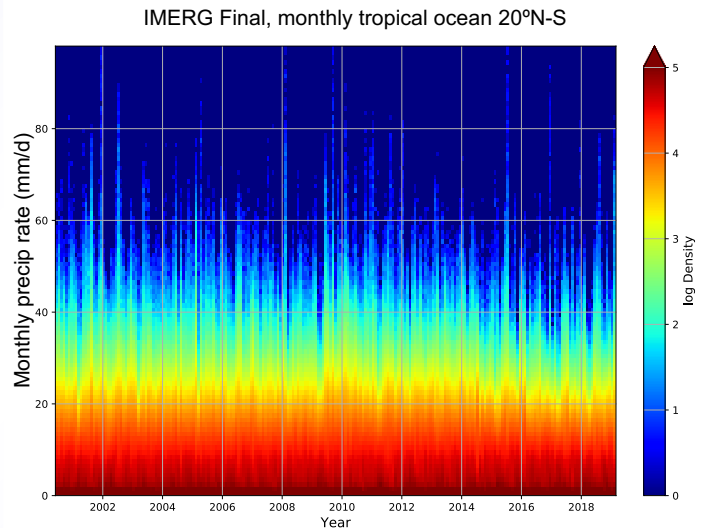- log(counts) to help draw out small values

Anomaly helps guide interpretation (bottom)

- log scale in both directions from zero
- filtered in time to emphasize main features

Initial impressions

- mid-to-high rates sometimes (2009-10) vary together, but not always (2006-07)
- lower rates tend to vary in the opposite direction
- start of GPM calibration (June 2014) seems to shift the PDF to lower rates
- persistent mid-range positive anomalies in 2009-14 remain to be explained

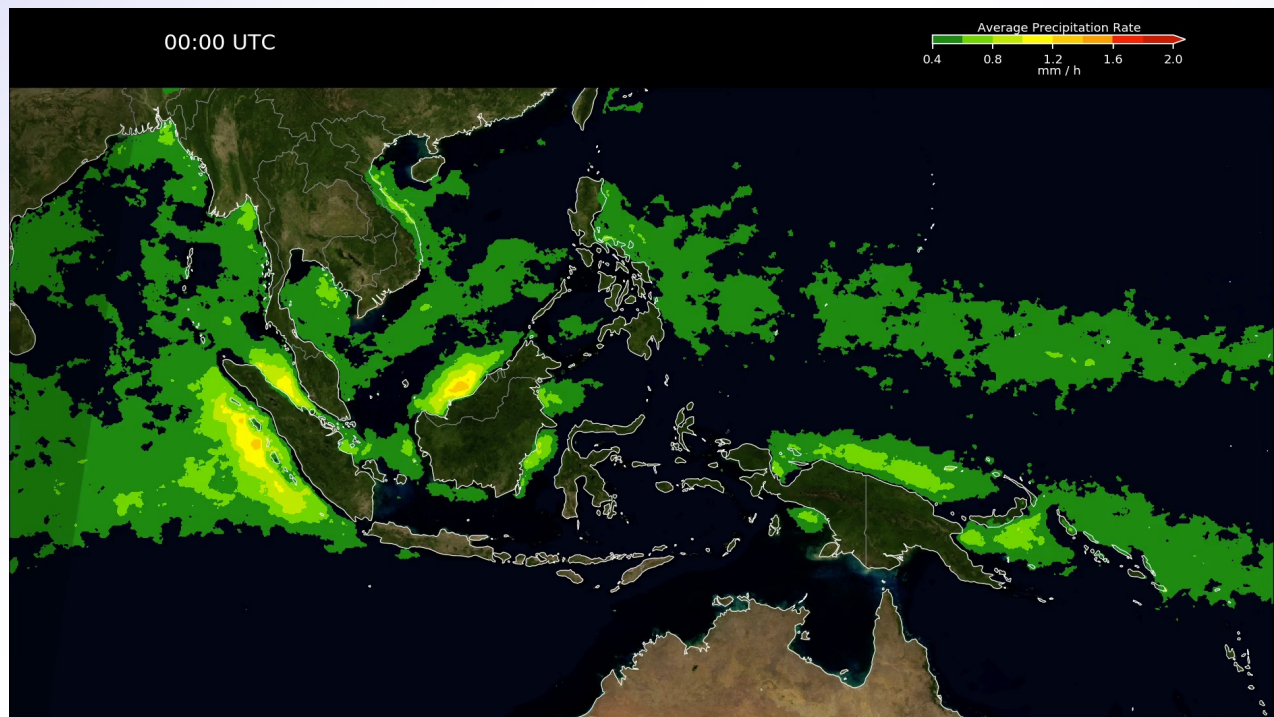This discussion will help determine reliability for trend analysis

Potter et al. (2020)

IMERG Final, monthly tropical ocean 20ºN-S

IMERG Final anomalies, monthly tropical ocean 20ºN-S
Savitzky-Golay filter window=5, polynomial order=3

Average September-November for 2001 to 2018, Late Run

- day/night shading
- Blue Marble land
- smoothed in space and time
  - even 18 years of seasonal data still has lumps

Reminiscent of TMPA, but

- more detailed, broader spatial coverage
- no interpolations between the 3-hourly times
- less IR-based precip used (which tends to have a phase lag)

00:00 UTC

Average Precipitation Rate

0.4 0.8 1.2 1.6 2.0
mm / h

J. Tan (USRA; GSFC)